# Signal penalties induced by different types of optical filters in 100 Gbps PM-DQPSK based optical networks

Xiaoyong Chen *, José A. Martín Pereda, Paloma R. Horche

*Departamento de Tecnología Fotónica y Bioingeniería, ETSI Telecomunicación-Universidad Politécnica de Madrid, Madrid, Spain*

A B S T R A C T

Optical filters are crucial elements in optical communication networks. However, they seriously affect the signal quality, especially in the concatenation condition. In this paper, we study and simulate the signal penalties induced by five types of filters, including Butterworth, Gaussian, Bessel, Fiber Bragg Grating (FBG) and Fabry–Perot (F–P) filters, in order to optimize the optical network performance. Signal penalties, including both filter concatenation effect and filter induced in-band and out-band crosstalk, are analyzed by eye opening penalty (EOP) and *Q*-penalty. Simulation results show that the Butterworth filter performs best among these four types of filters. Total *Q*-penalty induced by a Butterworth filter-based demultiplexer/multiplexer pair, considering both filter concatenation effect and crosstalk, is lower than 0.5 dB, when the filter bandwidth is in the range of 42–46 GHz. Simulations done in a 100 Gbps PM-DQPSK optical network indicate that the permitted cascaded number is 14 and 10 with respect to the case of filters aligned and misaligned, respectively. Penalties induced by laser frequency shift are investigated and the performance of the 3rd-order Butterworth filter is compared to the 4th-order superGaussian filter. Finally, discussions of optical filter performances, including insertion loss, reconfigurability and programmability, are presented.

*Keywords:*
Optical filter
Optical crosstalk
Signal impairment
Optical communication
Polarization multiplexed differential quadrature phase shift keying (PM-DQPSK)

## 1. Introduction

Optical networks are designed to keep optical signals in the optical domain, as long as possible, before the signal quality has been disturbed to a level where the optical-to-electrical-to-optical (O/E/O) regeneration is necessary [1–3]. As a consequence, optical cross-connects (OXCs) and reconfigurable optical add-drop multiplexers (ROADMs) are used to adding, dropping and switching channels from one optical fiber to another one in the network nodes. Usually, the conventional OXCs and ROADMs comprise multiplexer, demultiplexer and wavelength selective switch (WSS) modules. Multiplexers/demultiplexers and WSS are actually optical filters. Hence, filter performance is significantly related to the optical network performance, especially in the long-haul transmission networks.

Due to the undesirable design, optical filter not only induces crosstalk from the neighboring channels, but also leads to a filter concatenation effect when the signal passes through several filters. In addition, misaligned filter center frequencies will also further increase the filter-induced signal penalty.

Many previous papers have studied the effects induced by optical filters, including simulation of signal impairment originated by cascaded ROADMs with filter shape of Gaussian function [1]; signal distortion and crosstalk penalties induced by optical filters with filter shape of Butterworth function in 10 Gbps NRZ/RZ based optical

* Corresponding author. Tel.: +34 913 363 408; fax: +34 913 367 319.
*E-mail address:* xiaoyong.chen@alumnos.upm.es (X. Chen).

networks [2]; investigation of a cascade of 11 FBG filters with bandwidth of 50 GHz in a 20 Gb/s NRZ system [4]; and analysis of optical filter-induced loss ripple, group delay ripple and dispersion [5,6]. Moreover, impact of optical filters on advanced modulation formats has also been studied in recent years. Signal impairment caused by filter concatenation in coherent optical OFDM system has been reported by Chochol et al. [7], where filter shape of Gaussian function was studied. Impact of cascaded ROADM on mQAM optical signals employing Nyquist shaping has been presented by Filer and Tibuleac [8]. Performance tradeoffs of 120 Gb/s DP-QPSK in ROADM systems has also been reported by Filer and Tibuleac [9,10], where filter shape of the 4th-order superGaussian function was investigated. In addition, spectral modeling of Liquid Crystal on Silicon (LCoS) based programmable optical filters have been looked into by Pulikkaseril et al. (Finisar) [11,12], where filter shape of an error function-based model was studied. In [13], a ROADM with flexible bandwidth based on LCoS technology is presented, where the spectral function at $-3$ dB is approximated by a Gaussian filter and its tails by a Bessel filter.

It must be pointed out that almost all of the aforementioned works only discusses the performance of one kind of optical filter. Actually, there are many types of optical filter models that can be used to characterize the WSS channel shape in optical communication system. For example, Gaussian [1], Butterworth [2] and Bessel [14] optical filters can be a choice in characterizing the WSS channel shape. Tunable fiber Bragg grating (FBG) [15] and Fabry–Perot (F–P) [16] filters can also currently be used for wavelength selection.

Therefore, in order to optimize the performance of the optical networks, it is very important to look into the optical signal impairments caused by all of the aforementioned types of optical filters and also, estimate the number of concatenated filters allowed.

On the other hand, although the current 100-Gbps optical transport network (OTN) employs PM-QPSK signals, the 100 Gbps PM-DQPSK signal is a good candidate for the metro-area networks (MAN), due to the short-haul transmission, which will greatly mitigate the tolerance of the signals to the chromatic dispersion, polarization mode dispersion and fiber nonlinearities. In addition, the possibility of direct-detection used in the receiver end for PM-DQPSK signals detection can reduce the receiver complexity and the total cost, resulting in 100 Gbps PM-DQPSK-based optical networks easy to implement. These two factors make the PM-DQPSK signal an optimal candidate for MAN networks. Hence, it is significant to study the impact of different types of optical filters on the 100 Gbps PM-DQPSK signals, in order to optimize the 100 Gbps PM-DQPSK-based MAN networks.

In our previous work [17,18], we have studied filter concatenation effect induced signal impairment and crosstalk induced signal penalties by four types of filters, including Butterworth, Bessel, FBG and F–P filters, in 40 Gbps DQPSK and 100 Gbps PM-DQPSK single-channel systems. In this work, besides investigating the signal penalties originated by the filter concatenation effect and crosstalk, we also study the total signal penalty originated by optical filters at 100 Gbps PM-DQPSK-based optical networks in different cases, including optical filters aligned, misaligned, and laser frequency shift.

This paper is organized as follows. Section 2 analyzes filter induced optical signal impairments, including both filter concatenation effect and crosstalk. Simulation setup and analysis method are reported in Section 3, and simulation results are discussed in Section 4. Finally, discussions of optical filter performances are presented in Section 5 and conclusions are drawn in Section 6.

## 2. Optical filter induced signal impairments

### 2.1. Filter concatenation effect

As previously mentioned, an optical signal will be filtered several times before reaching the destination in optical networks. This is due to the fact that optical nodes include several optical filters. The more optical nodes the signal passes through, the worse the signal quality is. This can be understood by filter concatenation effect.

The effective transfer function of cascaded filters is the product of the individual filters transfer functions. Therefore, the total effective transfer function is much narrower than that of an individual filter, as the red line shown Fig. 1. Moreover, it will become narrower if the center frequencies of individual cascaded filters are not aligned perfectly. This situation corresponds to the green line in Fig. 1 and comes from the optical filter transfer function being non-ideal. By increasing the number of cascaded filters, the flat top region of the effective transfer function becomes smaller while the tail decay becomes steeper.

The filter performance is determined by both amplitude and phase transfer functions. Different types of filters have different transfer functions, resulting in different effects on the signals. Fig. 2 shows the amplitude and phase transfer functions of four types of filters. We can see that, the F–P filter not only has a flat transmission spectrum, but also has a large linear phase region. This means that the effect induced to the signal, in the case of only one filter in the channel, is smaller. However, the

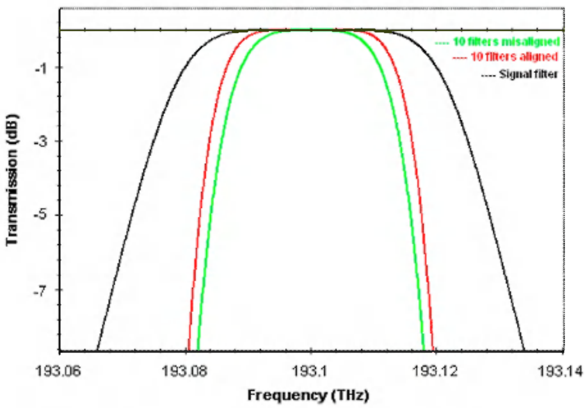


**Fig. 1.** Effective transfer functions of a single 3rd Butterworth filter and 10 cascaded filters aligned (red) and misaligned (green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

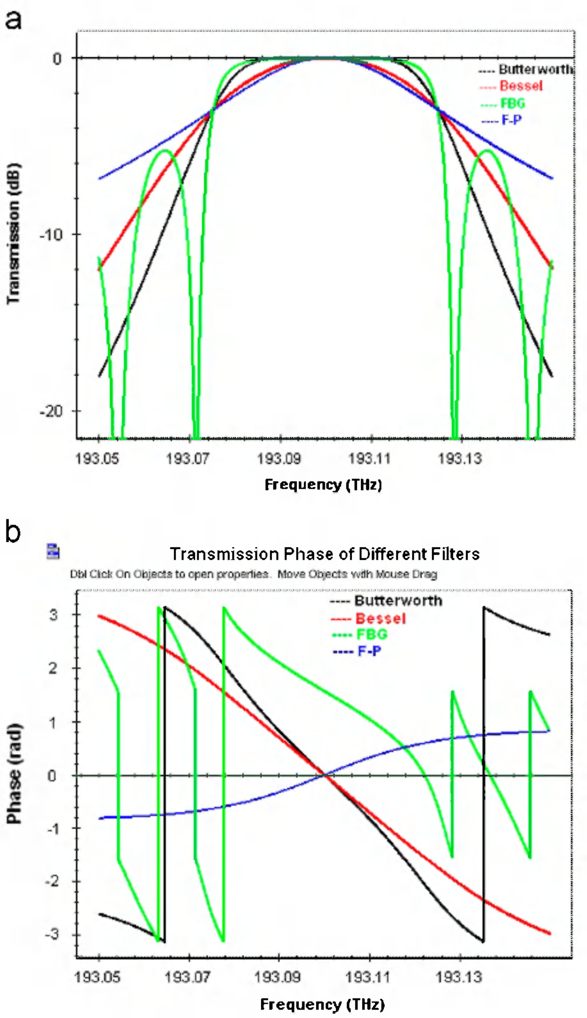


**Fig. 2.** (a) Amplitude transfer function of four kinds of filters; (b) phase transfer function of four kinds of filters.

small flat top region of transmission spectrum of F–P filter makes that the effective bandwidth decrease sharply in the case of filters being cascaded, as shown in Fig. 3. It can be seen that when twenty 50-GHz F–P filters are cascaded, the effective bandwidth is only 10 GHz. The flat top region of the transmission function in a Bessel filter is a little larger than that of F–P filter, and it also has a linear phase region as large as an F–P filter. Hence, it can be inferred that the Bessel filters perform better than F–P filters in cascaded condition, as will be demonstrated in the next section. Fig. 2a also shows that the Butterworth filter and FBG have very wide flat top region, leading to that the effective bandwidth decreases slowly in cascaded condition, as shown in Fig. 3. An effective bandwidth as wide as 28 GHz is obtained when 25 FBG or Butterworth filters are cascaded. However, the linear phase regions of phase transfer functions of FBG and Butterworth filters are narrower than that in Bessel and F–P filters; this will increase the effect on signals. Fig. 3 also depicts that the effective bandwidth become narrower when all cascaded filters are not perfectly aligned. It should be pointed out that the linear phase region narrows when the cascaded number increases.

### 2.2. Crosstalk

In addition to filter concatenation effect, filter induced crosstalk also severely aggravates the signal quality. Fig. 4 shows the principle of crosstalk induced by filters. As can be seen, some power is sent to the wrong channels when the signal passes through an optical filter, due to the non-ideal transmission function. In optical networks, filter induced crosstalk can be divided into two types of crosstalk: out-band and in-band crosstalk. These two types of crosstalk take penalties to the signals, especially the latter.

#### 2.2.1. Out-band crosstalk

Out-band crosstalk is the linear crosstalk suffered at the receiver by leakage of some power from adjacent channels into the main signal to be detected and it is introduced by an optical filter if its passband leaks other channels (see Fig. 4). This type of crosstalk only occurs at the final drop location of the channel, and the leaked power is at a different wavelength from the channel wavelength. In general, power penalty depends on the finesse of the filter. Usually, the leaked power from adjacent channels is very small and the corresponding induced signal penalty is also small.

#### 2.2.2. In-band crosstalk

In-band crosstalk is well recognized as a potentially serious impairment in optical networks with optical switching and configuration nodes, such as OXCs and ROADMs [1,2]. Usually, in-band crosstalk can be induced either by the optical switch fabrics in which a small fraction of a signal is sent to the wrong output port, or by the optical demultiplexers and multiplexers (DEMUX/MUX) employed in each optical node. Due to the fact that the emphasis of our work is filter induced signal penalty, we only concentrate on the DEMUX/MUX pair induced in-band crosstalk. In our case, in-band crosstalk is generated by the leakage of small amounts of signal power into different output ports of a demultiplexer and then further leakage of those small signal copies into the outgoing transmission fiber by the multiplexer at the node output side.

The in-band crosstalk caused by leaked power is determined by the effective bandwidth and the effective transmission function of a DEMUX/MUX pair. Thus, different types of filters can induce different leakages, leading to different in-band crosstalk. Fig. 5 shows crosstalk power leaked through an adjacent channel port for a DEMUX/MUX pair in a 100 Gbps PM-DQPSK based network. It is normalized to the transmission value at the filter center frequency. We can see that the Butterworth filter generates the least leakage among these four types of filters, while the F–P induced leakage is the maximum.

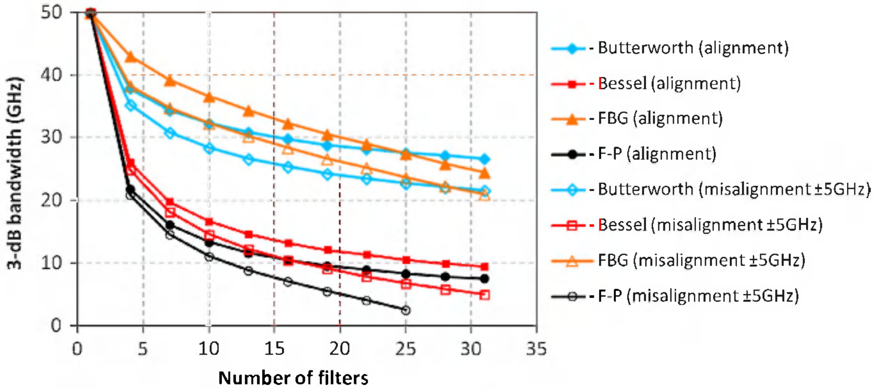


**Fig. 3.** 3-dB bandwidth as a function of number of filters.

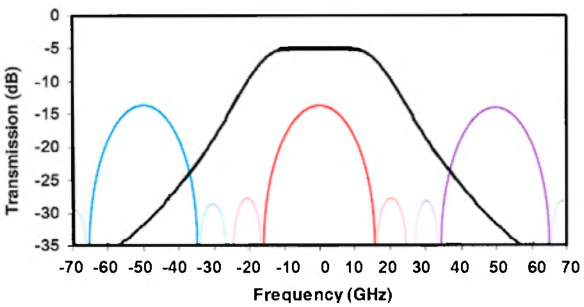


**Fig. 4.** Transmission function of an optical filter and the origin of crosstalk.

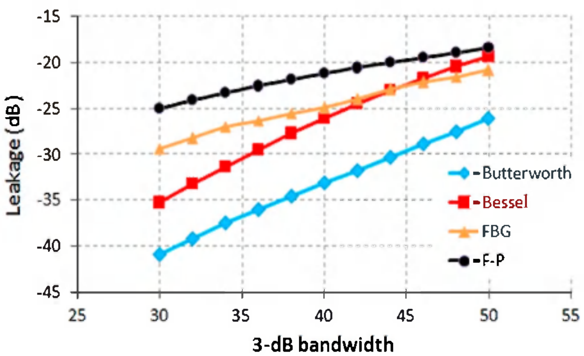


**Fig. 5.** Crosstalk power level as a function of 3-dB bandwidth.

As it is known, the variance of the digital "one" due to in-band crosstalk can be written as [2]

$$\sigma^2_{xt,1} = \eta^2 R^2 P_s \sum_{j=1}^{J} P_{xt,j} \cos^2(\varphi_j) \tag{1}$$

where $\eta$ is the ratio of the signal peak power in the "ones" to the average power, $R$ is the detector responsivity, $P_s$ is the average signal power, $J$ is the total number of crosstalk terms, $P_{xt,j}$ is the average crosstalk power of the $j$th corsstalk term,and $\varphi_j$ is the polarization angle difference between crosstalk term $j$ and the signal. This expression ignores beating effects between the crosstalk terms, because they are very small. We assume that the effective adjacent and nonadjacent channel crosstalk values through a DEMUX/MUX pair are $\varepsilon_{adj}$ and $\varepsilon_{nonadj}$, respectively. Also, assuming that the signal and all crosstalk terms are due to copolarization, the variance of the "ones" after passage through $K$ optical nodes generated by DEMUX/MUX pairs and switch fabric crosstalk terms can be expressed as

$$\sigma^2_{xt,1} = K\eta^2 R^2 P_s^2 \left[2\varepsilon_{adj} + (M-3)\varepsilon_{nonadj} + \varepsilon_{switch}\right] \tag{2}$$

where $\varepsilon_{switch}$ is the optical switch fabric induced crosstalk, and $M$ is the number of channels.

## 3. Simulations setup and analysis method

In order to verify the optical filters induced signal penalties, we built a simulation setup as shown in Fig. 6. The signals used in the simulation were 100 Gbps PM-DQPSK signals. The transmission spans $N$ is varied from 0 to 30, and each span is composed by a single mode fiber (SMF), a dispersion compensation fiber (DCF), two erbium-doped fiber amplifiers (EDFAs) and one ROADM. The EDFAs were used to compensate the power loss induced by ROADM, single mode fiber (SMF) and dispersion compensating fiber (DCF). The power launched into the DCF, which was used to compensate the SMF induced dispersion, was kept lower than −4 dBm for avoiding introducing non-linear effects. The signals were separated then by a demultiplexer, and detected by the PM-DQPSK receivers. It should be indicated here that the PM-DQPSK receivers used in the simulation were incoherent receivers based on four delay interferometers [19]. Finally, the detected signals were analyzed by bit error rate (BER) analyzers. The simulation parameters are indicated in Table 1.

We analyze the signal impairment from eye-opening penalty (EOP) and Q-penalty. The eye opening parameter is defined as the intensity difference between the minimum "ones" value and the maximum "zeros" value without noise. The EOP and Q-penalty is defined as the difference between the normalized eye opening after passage through an optical link without any filters and the normalized eye opening after passage through the same optical link with a given number of filters. The eye opening parameter, EOP and Q-penalty can be described by the following functions, respectively [20].

$$\text{Eye Opening} = V_1 - V_0 \tag{3}$$

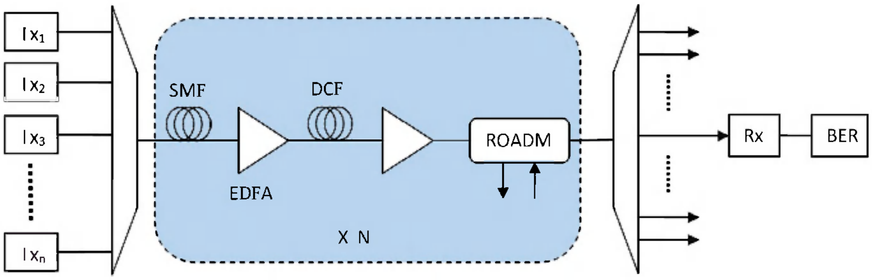


**Fig. 6.** Simulation setup: (a) single-channel; (b) multi-channel. Tx: transmitter; Rx: receiver; BER: Bit Error Rate Analyzer; EDFA: erbium-doped fiber amplifier; SMF: single mode fiber; DCF: dispersion compensation fiber.

**Table 1**
Simulation parameters.

| Name | Parameter | Unit | Value |
|---|---|---|---|
| Filters (Butterworth, Bessel, FBG and F–P) | Insertion loss | dB | 5 |
| EDFA | Gain | dB | 15 |
| | Noise figure | dB | 5 |
| SMF | PMD | ps/km | 0.02 |
| | Chromatic dispersion | ps/nm km | 16.0 |
| | Dispersion slope | ps/nm$^2$ km | 0.075 |
| | Attenuation | dB/km | 0.2 |
| | Length | km | 90 |
| DCF | PMD | ps/km | 0.05 |
| | Chromatic dispersion | ps/nm km | −48 |
| | Dispersion slope | ps/nm$^2$ km | −0.15 |
| | Attenuation | dB/km | 0.26 |
| | Length | km | 30 |

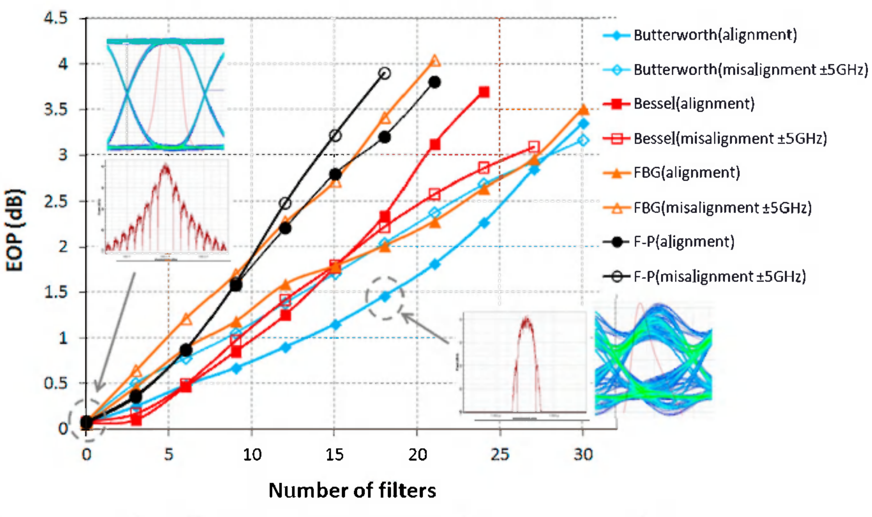


**Fig. 7.** EOP as a function of cascaded filters in the 100 Gbps PM-NRZ-DQPSK system with (a) all the filters' center frequency aligned and (b) filters' center frequency misaligned of +5 GHz.

$$EOP = 10\log\left(\frac{V_{u,1}-V_{u,0}}{V_{d,1}-V_{d,0}}\right) \tag{4}$$

$$Q-\text{penalty} = 20\log\left(\frac{V_{u,1}-V_{u,0}}{V_{d,1}-V_{d,0}}\right) \tag{5}$$

where $V_1$ is the voltage level of the minimum "1" rail at the eye center, and $V_0$ is the voltage level of the maximum "0" rail. The subscript "$u$" represents the undistorted state of the signal and "$d$" represents the distorted state of the signal.

Therefore, in order to calculate the EOP or Q-penalty, we should first calculate the eye-opening for a given system in the absence of filters, and then obtain a new eye-opening which includes filters. The difference between these two values is the EOP or Q-penalty originated by filters.

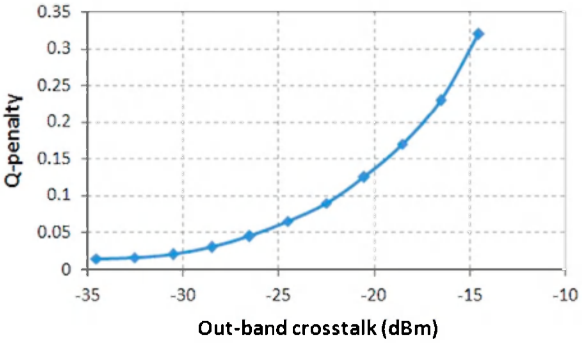


**Fig. 8.** Q-penalty as a function of out-band crosstalk level.

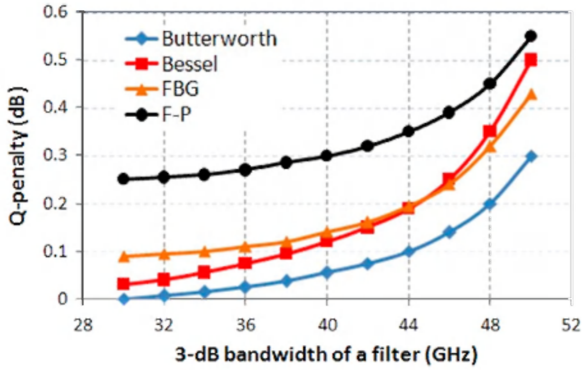


**Fig. 9.** Q-penalty induced by In-band crosstalk as a function of the bandwidth of the filter used in the DEMUX/MUX.

## 4. Simulation results

Several simulations were done to verify penalties induced by optical filters, including penalties induced by filter contenation effect and crosstalk, total Q-penalty induced by optical filters in alignment and misalignment, and total Q-penalty induced by laser frequency shift.

### 4.1. Filter concatenation effect induced signal impairment

In this subsection, we analyze the signal impairment originated by the filter concatenation effect. Therefore, only one signal was used in the simulation. The filters employed in this simulation have a bandwidth of 50 GHz. Results are shown in Fig. 7. When all filters are exactly aligned with the laser frequency, the Butterworth filter shows the best performance among these four types of filters. With 1-dB EOP, about 12 Butterworth filters can be cascaded in the channel, while the permitted cascaded number for FBG, F–P and Bessel filter are 7, 6 and 10, respectively. When all filters are randomly misaligned with the laser frequency (+5 GHz), signal impairments caused by FBG and Butterworth filters become much more severe, compared with the case of all filters being aligned. Only 5 FBG and 9 Butterworth filters can be cascaded with 1-dB EOP. The Bessel and F–P filters are not very sensitive with frequency misalignment. The permitted cascaded number is almost the same as the case of frequencies alignment, under the limitation of 2-dB EOP. The insets in Fig. 7 shows filter concatenation effect induced signal impairments in frequency domain (signal spectrum) and time domain (eye diagram).

### 4.2. Crosstalk induced signal penalties

As discussed in Section 2, filter induced crosstalk can be divided into out-band and in-band crosstalk. The out-band crosstalk occurs only once, at the final drop location of the channel, and the crosstalk terms are different wavelengths from the main signal. Because the leakage from other channels is very small, Q-penalty induced by out-band crosstalk is also very small. Fig. 8 shows the out-band crosstalk induced Q-penalty as a function of out-band crosstalk level. As can be seen, Q-penalty caused by out-band crosstalk is lower than 0.15 dB, when the crosstalk level is lower than −20 dBm. Combining with Fig. 5, it can be see that, although F–P filter induces the highest leakage among four types of filters, Q-penalty generated by F–P filter induced out-band crosstalk is also very small. Furthermore, it should note that the out-band crosstalk can be further reduced by the optical filter in front of the receiver.

Compared with out-band crosstalk, in-band crosstalk severely affects the signal quality, even if the leakage is very small. To analyze the relationship between filter bandwdith and in-band crosstalk induced Q-penalty, filter bandwidth was varied from 28 to 50 GHz. Simulation results are shown in Fig. 9. It can be seen that the Q-penalty increases as the filter bandwidth increases; this corresponds to the leakage shown in Fig. 5. The results indicate too that the Butterworth filter based DEMUX/MUX pair, performs best among these four types of filters. When the bandwidth is narrower than 44 GHz, the Q-penalty induced by in-band crosstalk is lower than 0.1 dB. In addtion, combining with Figs. 5, 8 and 9, we can see that out-band crosstalk induced Q-penalty is much lower than that caused by in-band crosstalk. For example, when the leakage is −30 dBm, the out-band crosstlk induced Q-penalty is ~0.025 dB; this compares with ~0.1 dB caused by in-band crosstalk.

### 4.3. Q-penalty induced by OXC

Optical networking ultimate goal is the development of a full optical Internet, where signals carried within the network never leave the optical domain. A first important step in this direction is to have optical networks transparent, at least for data. A network is referred to as transparent when its constituent nodes are all-optical, such as ROADMs and OXCs where no conversion into the electrical domain is performed. Therefore, it is significant to study the Q-penalty from the optical nodes.

Given the signal impairment and crosstalk penalties analyzed above, we have built an optical system to test the total Q-penalty caused by a DEMUX/MUX pair based OXC. The system contained 8 50-GHz channels, and all the signals were 100 Gbps PM-DQPSK signals. The simulation results are shown in Fig. 12. As can be seen, the total Q-penalty induced by F–P or FBG filters based OXC is much larger than the one caused by Bessel or Butterworth filters

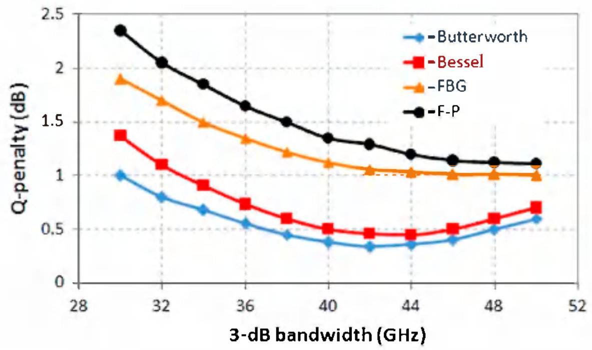

**Fig. 10.** Total Q-penalty induced by an OXC based on different types of filters.

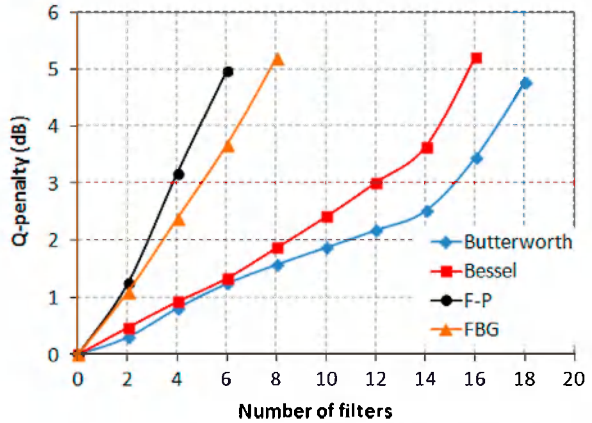

**Fig. 11.** Q-penalty as a function of number of filters, with all filters in alignment.

based OXC. Q-penalty induced by F–P or FBG filters based OXC is larger than 1-dB along the studied filter bandwidth. Also, the results show that the Q-penalty caused by Butterworth or Bessel filters based OXC first decreases with the bandwidth and then increases with the bandwidth. This indicates that total Q-penalty is determined by both filter concatenation effect and crosstalk. Fig. 10 depicts that, when the bandwidth is in the range of 40–46 GHz, the total Q-penalty caused by Butterworth or Bessel filters based OXC is lower than 0.5 dB.

### *4.4. Q-penalty induced by optical filters aligned and misaligned in optical networks*

In this subsection, we determine the Q-penalty induced by OXCs with all filters both in alignment and misalignment.

The simulation system is the same as shown in Fig. 6, and the number of channels is 32, with channel spacing of 50-GHz. The filters, used in these simulations, have 3-dB bandwidth of 42-GHz, which corresponds to the optimal bandwidth analyzed in Section 4.3, as well agree with the real conditions [3]. Simulation results of all the filters aligned perfectly are shown in Fig. 11. As can be seen, Butterworth filter performs best among four types of filters, which is in agreement with the analysis presented in the former sections. With 3-dB Q-penalty, 14 Butterworth filters (corresponding to 7 OXCs) can be cascaded in the optical

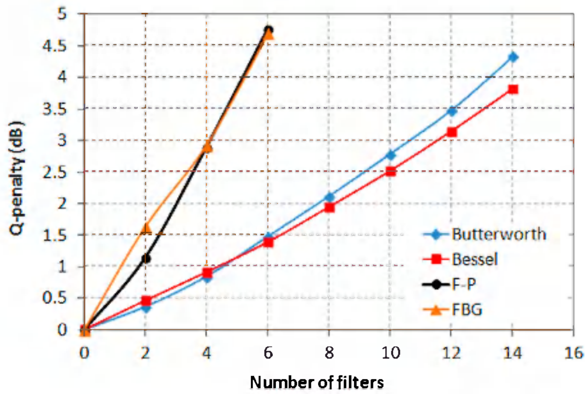

**Fig. 12.** Q-penalty as a function of filter number, with all filters in misalignment.

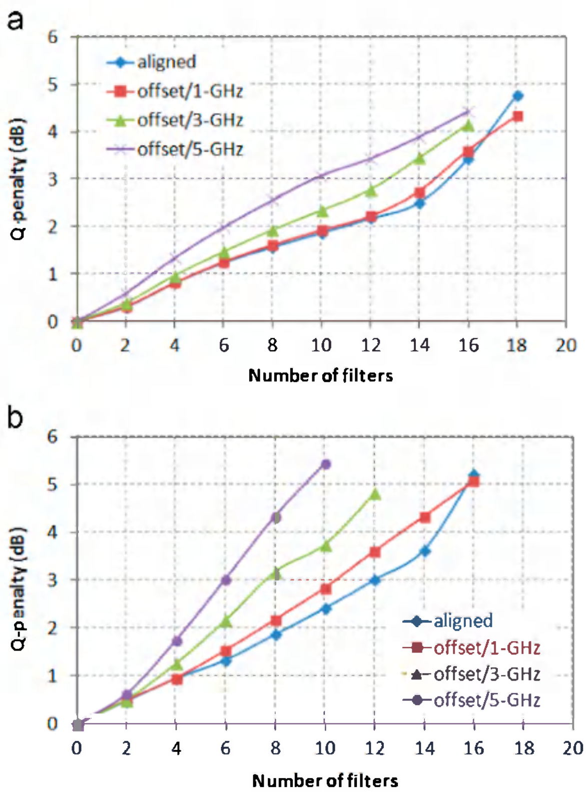

**Fig. 13.** Q-penalty induce by laser frequency shift from filter center frequency: (a) Butterworth; (b) Bessel.

networks. The permitted number is reduced to 12, 4 and 4 for Bessel, F–P and FBG filters, respectively. In comparison with Fig. 7, where signal impairment was only induced by filter concatenation effect, it is obvious that the filter number allowed using in optical networks is reduced. This is because besides filter concatenation effect, filter induced crosstalk also aggravates the signal quality. It should be noted that the value of 3-dB Q-penalty in our simulation means to reach bit rate error (BER) of $10^{-3}$.

To further investigate the filter induced Q-penalty, the tolerance to the filter misalignment was also studied in the simulation. It was assumed the worst case for the filter

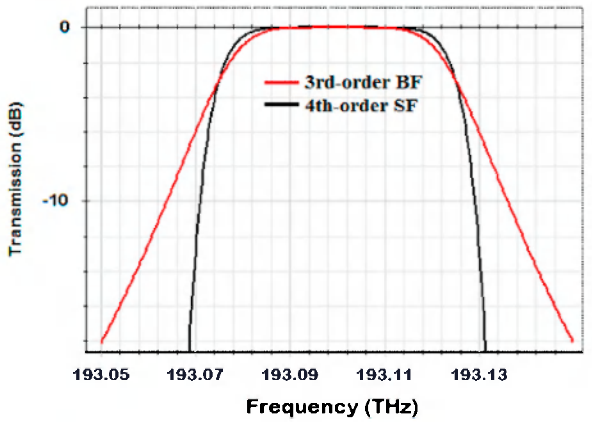


**Fig. 14.** Transmission spectrum of 4th-order supergaussian filter (SF) compared with 3rd-order Butterworth filter (BF).

misalignment. This means that for each OXC node, the first interleaver was centered at +5 GHz of the channel spacing while the second interleaver was at −5 GHz. The obtained results are depicted in Fig. 12. It can be seen the Bessel filter even performs slightly better than Butterworth filter. The permitted number using in optical networks is almost the same as the case of filters in alignment. ∼12 Bessel filters can be cascaded in optical networks, with 3-dB Q-penalty.

The simulation results, including both cases of filters in alignment and misalignment, imply that the 50-GHz FBG and F–P filters are not suitable for using in 100 Gbps PM-DQPSK optical networks, due to the large signal penalty induced by these two types of filters.

### 4.5. *Q-penalty induced by laser frequency shift*

Finally, we also test the Q-penalty induced by laser frequency shift from the filter center frequency. As it was reported in Section 4.4, Butterworth and Bessel filters are the more suitable for being employed in optical networks. Therefore, we only study these two types of filters in this section. In the simulation, all of the filter center frequencies were assumed to be aligned, and the laser frequency shifts were set to be 1, 3 and 5 GHz.

Fig. 13 shows the simulation results of the Q-penalty induced by optical filters with different laser frequency shift values. We can see that Q-penalty increases as the laser shift increases, especially for the Bessel filter. When the laser shift is 1-GHz, Q-penalty induced by both types of filters is very small, almost the same as that without laser shift. However, when the laser shift is 5-GHz, much larger Q-penalty is induced using Bessel filter by compared with the Butterworth filter. In this case, only 6 Bessel filters are allowed to be cascaded in the networks while the permitted value is 10 for Butterworth filter, with 3-dB Q-penalty. The laser frequency shift originated signal impairment can be understood that the optical signal is distorted as it passes through the side of the filter passband. If we consider filter frequencies misaligned, a larger Q-penalty will be induced.

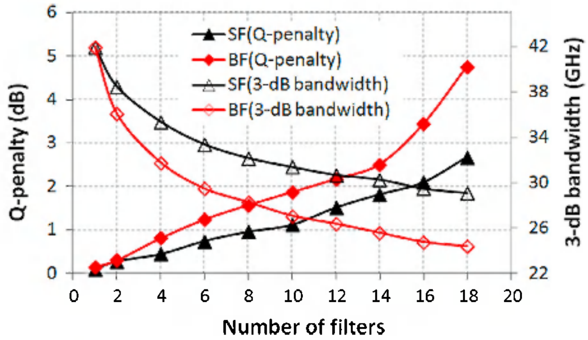


**Fig. 15.** Q-penalty caused by 4th-order supergaussian filter (SF) compared with the 3rd-order Butterworth filter (BF) in an 8-channel system.

### 4.6. *Comparison between 3rd-order Butterworth and 4th-order superGaussian optical filters*

In order to complement the work presented in this paper, we will discuss signal impairment caused by the 4th-order superGaussian optical filter compared with the 3rd-order Butterworth optical filter.

The transfer function of the 4th-order superGaussian filter is shown in Fig. 14. As can be seen, it have wider flat top region but steeper skirts, in comparison with the 3rd-order Butterworth filter. This means that the 4th-order superGaussian filter can provide wider passband but clips signal spectrum severely. Note, however, that less crosstalk will be induced due to the steeper skirts.

Fig. 15 shows the total Q-penalty caused by 4th-order superGaussian filters compared with the 3rd-order Butterworth filters in an 8-channel system. Note that in this simulation it is assumed that all filters are ideally aligned. It can be seen that the 4th-order superGaussian filter performs better than the 3rd-order Butterworth filter. With 2-dB Q-penalty,∼4 more 4th-order superGaussian filters can be cascaded in the system. This is because the cascaded 4th-order superGaussian filters can provide wider bandwidth, which is also shown in Fig. 15. Moreover, less crosstalk is induced due to the steeper edges of the transfer function.

Additionally, it should be noted that Pulikkaseril et al. [11,12] have pointed out that the error function-based model can provide a much more accurate spectrum compared to the superGaussian model for evaluating the WSS channel shapes.

## 5. Discussions of optical filter performances

### 5.1. *Insertion loss*

Insertion loss is one of the more important characteristics of an optical filter. In this work, the optical filter-induced insertion losses are compensated by the EDFAs, which can be seen in the simulation setup shown in Fig. 6. In comparison with the filter concatenation effect and crosstalk-induced signal impairments, which cannot be easily remedied through amplification or by other means, signal penalty caused by insertion loss can be compensated by optical amplifiers such as EDFAs, but at the cost of

**Table 2**
Insertion loss of optical filter.

| Optical filter | Insertion loss |
|---|---|
| Thin film filter (Butterworth and Bessel filter models) | < 1 dB |
| FBG | < 0.5 dB |
| F–P | < 0.5 dB |

added noise. Since the focus of this work is the filter concatenation effect and crosstalk-induced signal impairments, penalty caused by filter-induced insertion loss will not be discussed independently here. In addition, with the commercial optical filters in use, the insertion loss (without considering the connector) is low. Insertion losses of different types of optical filters are shown in Table 2.

### 5.2. Reconfigurability

Reconfigurability of an optical filter refers to the ability to select the desired wavelengths to be dropped and added, as opposed to having to plan ahead and deploy appropriate equipment. Reconfigurability is the key characteristic of the ROADMs. If an optical filter is able to perform some type of reconfigurability, it can be employed as a passive (de)multiplexer filter and as the optical switch module used in the conventional ROADMs This simplifies the structure and deserves analyzing the reconfigurability of each optical filter.

The Butterworth and Bessel filter models are commonly used for describing the thin film filters, which are widely employed in optical communication systems. Nowadays, thin film filter is a very mature technology, and thin film filters with tunability and switchable ability have been realized [21]. It can be known that the swichable ability is realized based on a combination of several dielectric films with several thermo-optic semiconductor film. By changing the temperature, the transmission function of the filter can be varied correspondingly.

Also, the FBG [15] and F–P [16] optical filters with tunability have been reported and commercialized. In comparison with the FBG, the F–P has wider wavelength and bandwidth tunable range.

### 5.3. Programmability

The obvious benefits of the aforementioned optical filters, thin film, FBG and F–P, are their high extinction ratio, low-cost and low insertion loss. Moreover, they are commercialized. The drawback is that they are not flexible. This fact will limit their applications in future optical networks. In order to make them suitable for using in future flexible-grid optical networks, programmable optical filters based on Liquid Crystal on Silicon (LCoS) technology are widely studied and used for WSS in recent years [13,22,23]. This has been due to their high-flexibility, high-resolution, high-efficiency and low-cost.

Finally, although the programmability can change very easily the center frequency and the bandwidth of an optical filter, it will not affect the filter shape. In other words, whether an optical filter is programmable or not, its transmission function can be described by a (quasi) filter model.

## 6. Conclusions

In this paper, we have studied and simulated signal penalties due to four types of optical filter models, including Butterworth, Bessel, F–P and FBG filters. Filter induced signal penalties are theoretically analyzed from filter concatenation effect and filter induced in-band and out-band crosstalk. Simulations were done to test the filter concatenation effect induced signal impairment, crosstalk induced signal penalties, and total filter induced *Q*-penalty. Simulation results shows that Butterworth filter performs best among four types of filters. Study of filter concatenation effect indicates that 12 Butterworth filters with filter center frequencies aligned can be cascaded, and 9 with filter center frequencies misaligned of $+5$ GHz, with 1-dB EOP. Investigation of crosstalk shows that in-band crosstalk seriously affect the signal quality. When the bandwidth is narrower than 44 GHz, in-band crosstalk induced by a Butterworth filters based DEMUX/MUX pair is lower than 0.1 dB. In addition, simulation results, considering both filter concatenation effect and crosstalk, indicate that total *Q*-penalty caused by a Butterworth filter (or Bessel filter) based OXC can be lower than 0.5 dB, when the filter bandwidth is in the range of 40–46 GHz.

Moreover, simulations were done in a 100 Gbps PM-DQPSK based optical network to test the filter performance. With 3-dB *Q*-penalty, only 14 Butterworth filters can be cascaded in the case of filters aligned, while 10 filters are allowed in the case of filters misaligned. Furthermore, simulations were done by considering the laser frequency shift; the results indicate that a large extra *Q*-penalty is introduced when the shift is 5-GHz.

In addition, comparison between the 4th-order super-Gaussian and 3rd-order Butterworth filters shows that less *Q*-penalty is induced by the 4th-order superGaussian filter.

Finally, discussions of optical filters, including insertion loss, reconfigurability and programmability, are reported. Compared to the non-programmable filters such as F–P and FBG optical filters, novel optical filters based on the LCoS technology shows very good programmability and hence they could be employed in future flexible optical networks.


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